CALCULATION OF SAFE SPEED AND MINIMALLY ADMISSIBLE DISTANCE OF CLOSING OF SHIPS DURING RADAR INFORMATION USAGE

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Abstract: Exceeding the safe speed and the minimum allowable distance when ships ap-proach each other is considered as one of the main reasons for their collision, especially when using radar information when sailing in reduced visibility or in confined areas. When assigning a safe speed, among other factors, the rules recommend to take into account the state of visibility of the maneuverable capabilities of the ship, especially the distance required to completely stop the ship, as well as the characteristics, efficiency and limitations of radar equipment. But, besides the quality recommendations in the COLREGs, there are no quantitative estimates of the safe speed and excessive convergence of the ships. Each navigator subjectively assigns a safe speed and determines the minimum allowable approach distance for ships. Therefore, the development of a universal method for calculating safe speed and the minimum allowable distance when using radar information is relevant, and the method itself is effective when used on ships, especially when sailing in difficult navigation areas and with limited visibility. The developed method allows to automate the choice of safe speed and eliminate the subjective fac-tor when it is appointed navigator.
Keywords: navigation safety, international regulations for preventing collisions at sea (COLREGs), maneuvering of ships.

1. Introduction

In spite of the continuous improvement of navigation equipment and tightening control over the implementation of the International Conventions, situations of excessive convergence of ships and collision of ships continue to be a major issue for navigation safety. According to official statistics, 89 clashes took place in 2017 [1].

The International Regulations for Preventing Collisions at Sea, 1972 (COLREGs) introduce such interconnected concepts as “safe speed” and “excessive convergence of ships.”

When designating safe speed among other factors, rules are recommended to take into account the state of visibility of the maneuverability of the ship, especially the distance required for a complete stop of the ship, as well as the characteristics, efficiency and limitation of radar equipment.

COLREGs strongly recommend the use of radar equipment to determine excessive convergence and the risk of collision of ships, subject to compliance by the navigator/operator with any restrictions imposed on the radar [2]. In addition to the qualitative recommendations in the COLREGs there are no quantitative estimates of safe speed and excessive convergence of ships. Each navigator subjectively assigns a safe speed and defines the minimum allowable approach distance of ships [3]. Because of this, in almost every case of collisions of ships, the main reasons are a significant excess of safe speed and a lowered distance of permissible approach of ships.

2. Methods

A very large number of publications devoted to the study of errors of technical means in determining the elements of the movement of dangerous ships and the appointment of the minimum allowable distance of approach to them. The situations of excessive rapprochement of the ships and the adoption of the most accurate solution for the safe divergence of the ships are considered quite fully [4]. Navigation equipment as a complex of automatic motion control systems of the ship are considered in detail [5], as the most complete source [6] and are given in [7]. When choosing a safe speed and minimum-acceptable approach of ships, it is necessary to take into account the characteristics of active braking, braking and acceleration of the ship [8–10]. However, in the cited publications [4–6] there is no formulation and solution of the problem of the mutual dependence of the safe speed and the minimum allowable distance of approach of ships.

The aim of the article is development of a universal method for calculating the safe speed and the minimum allowable distance when using radar information.

3. Results

The minimum allowable distance will be determined by the radius of the danger zone of approach of ships, $R_{d.z.}$.

When using a radar station (radar), the radius of the danger zone of approach of ships can be determined from the following expression:

$$R_{d.z.} = a + 2S_v. \tag{1}$$

Whence the maximum safe speed should be considered such a speed at which the stopping distance will be equal to:

$$S_v = \frac{1}{2}\left(R_{d.z.} - a\right), \tag{2}$$

where $R_{d.z.}$ – radius of the danger zone; S_v – length of the stopping distance of the ship at the initial speed v; a – radar parameter.

As can be seen from formulas (1) and (2), the radius of the danger zone and the magnitude of the safe speed depend on the braking characteristics of the ship and the radar parameter a, which should take into account the technical capabilities of the radar to detect the danger of the echo of another ship entering the danger zone. Quantitatively, the parameter a is expressed by distance, so its value can be represented as a dependency:

$$a = V_0 T, \tag{3}$$

where V_0 – relative speed of approach of the ships; T – observation time required to detect a dangerous approach of ships with the required accuracy.

The shortest distance to approach ships is determined by the formula given in [7]:

$$d_{sh} = d^2 \frac{\theta'}{V_0}, \tag{4}$$

where d_{sh} – the shortest approach distance; d – detection range of threatening ship; θ' – rate of bearing change.

The error in determining the shortest approach distance of ships will occur mainly due to inaccuracies in determining the rate of bearing change, since the distances are measured using radar relatively accurately. If in the presence of the danger of collision of ships the condition $d^2 \gg d_{sh}^2$ is satisfied, then the relative speed of approach of the ships becomes close to the radial one and can be measured on the radar screen with great accuracy. Given these circumstances, the error in the shortest distance will be equal to:

$$\delta_{d_{sh}} = d^2 \frac{\delta\theta'}{V_0}. \tag{5}$$

From where

$$V_0 = d^2 \frac{\delta\theta'}{\delta_{d_{sh}}}. \tag{6}$$

For radars operating in the centimeter wavelength range, the standard error in the rate of change of the bearing is: 60×10^{-6} radian/s (about 0.2 degrees/min.) [3]. As a marginal error of the shortest distance, ±1 mile can be taken, then the uncertainty of the side of the divergence of the ships will be completely excluded.

After substituting these values in the formula (6), let's obtain:

$$V_0 = d^2\left(\frac{60\cdot 10^{-6}\cdot 3600}{1{,}0}\right) = 0{,}22d^2, \tag{7}$$

where V_0 – relative speed in the nodes.

The error in the rate of bearing change is determined by the formula obtained in [3]:

$$\delta_{\theta'^2} = \delta_{\theta^2}\frac{12}{NT},$$

from where

$$T = \frac{\delta_\theta}{\delta_{\theta'}}\sqrt{\frac{12}{N}}, \tag{8}$$

where δ_θ – standard error in the bearing, equal to 0.018 radian (about 1 degree); $\delta_{\theta'}$ – error in the rate of bearing change, equal to 60×10^{-6} radians/s; N – the number of marks of the echo signal during the observation time, depending on the speed of antenna rotation.

Substituting these values into formula (8), let's obtain:

$$T = \frac{0{,}018}{60\cdot 10^{-6}}\sqrt{\frac{12}{N}} = \frac{1038}{\sqrt{N}}. \tag{9}$$

The rotation speed of ship radar antennas is never less than 15 rpm, so the value of N can be obtained from the expression

$$N = \frac{1}{4}T. \tag{10}$$

Substituting expression (10) into formula (9), let's find the minimum observation time for the given conditions:

$$T = \sqrt[3]{4\cdot 1038^2} = 163s = 0{,}045\,\text{min}. \tag{11}$$

Express the parameter a through the detection range of the echo signal:

$$a = V_0\cdot T = 0{,}22d^2\cdot 0{,}045 = 0{,}01d^2. \tag{12}$$

Taking into account this expression, formula (1) takes the following form:

$$R_{d.z.} = 0{,}01d^2 + 2S_v \tag{13}$$

and correspondingly,

$$S_v = \frac{1}{2}\left(R_{d.z.} - 0{,}01d^2\right). \tag{14}$$

The effect of parameter "a" on the radius of the danger zone is schematically shown in **Fig. 1**. Due to the presence of errors in the assessment of the risk of collision, the position of the target on the radar screen can be represented as a shaded area of a circle with a radius numerically equal to the parameter a. Since the parameter a is a function of the distance at which the definition of a collision hazard begins, as the distance decreases, the echo area will decrease. To ensure that the echo of another ship will pass from the observer's ship at a distance of at least two stopping distances, the parameter value should be added to this distance.

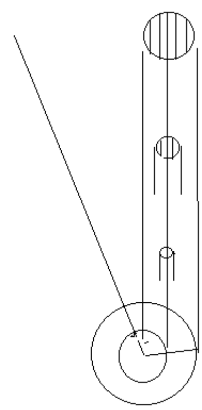

Fig. 1. Influence of parameter "a" on the radius of the danger zone

4. Discussion of results

Let's consider examples of calculating the radius of the danger zone and stopping distance at a given speed for a particular ship, the calculation of the braking characteristics of which is given in [8–10].

Let's present dependencies $S = f(V)$ and $V = f(S)$, when braking the ship for full reverse, in the form of analytical expressions:

$$S=0{,}07931+0{,}6263V-0{,}01496V^2, \tag{15}$$

$$V=0{,}426+0{,}91S+0{,}262S^2, \tag{16}$$

where S – in cable; V – in knots.

Example 1. The ship follows the open sea, far from the coast, in conditions of reduced visibility. The displacement of the ship is 22100 tons, the speed is 14 knots (full maneuverable advance).

According to the formula (15), let's calculate the stopping distance when the thruster is reversed for full reverse:

$$S=0{,}07931+0{,}6263\times 14-0{,}01496\times 196=5{,}9 \text{ cable}=0{,}59 \text{ miles}.$$

Radar detection range of ships is 7 miles. Counting the radius of the danger zone:

$$R_{d.z.}=0{,}01\times 7^2+2\times 0{,}59=1{,}67 \text{ miles}.$$

Example 2. The ship should be in narrowness with reduced visibility. The range of divergence from ships is limited to

0.9 miles, and the target detection range is limited to a five-mile radar scale. Based on these conditions, it is required to determine the safe speed.

According to the formula (2) let's find the stopping distance:

$$S_v = \frac{1}{2}\left(0{,}9 - 0{,}01 \cdot 5^2\right) = 0{,}32 \text{ miles=3,2 cables.}$$

At S_v=3.2 cables, the safe speed will be equal to:

V=0,426+0,9101×3,2+0,262×10,24=6,0 knots.

If, however, for any reason, the observer's ship cannot prevent excessive approach to another ship or if it hears a sound foggy signal ahead of its beam, then, according to Rule 19 of the COLREGs, it should reduce the stroke to the minimum until it passes collision hazard.

As a result of research, an analytical relationship is obtained between the safe speed and the minimum allowable approach distance of ships when using radar information. The developed method allows to automate the choice of safe speed and eliminate the subjective factor when it is appointed by navigator.

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